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ACOUSTIC VIBRATION AND STRENGTH ANALYSIS PROGRAM \(AVAST\) USER'S MANUAL \(VERSION 6.1\)

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D.P. Brennan — M.W. Chernuka

MARTEC Limited
1888 Brunswick Street, Suite 400
Halifax, Nova Scotia, Canada
B3J 3J8

CONTRACTOR REPORT

Prepared for

Defence Research Establishment Atlantic

Centre de Recherches pour la Défense Atlantique

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ABSTRACT - AVAST

A user's manual for finite element/boundary element program AVAST is presented. A brief introduction to the procedures incorporated into AVAST is given. The various analysis options are described and operating instructions, including a detailed description of data input and running procedures for RISC-based computer systems, are provided.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Summary of the AVAST System

The AVAST suite of programs have been developed as part of a DREA/MARTEC collaborative investigation into the numerical prediction of acoustic radiation and scattering from submerged elastic structures immersed in either full-space, half-space, or finite depth fluid domains [1-5]. Given a description of the structure and the properties of the surrounding fluid, AVAST solves for the fluid pressures and structural displacements on the wetted structural surface. This is achieved by matching at the fluid/structure interface a boundary element model of the exterior acoustic fluid field with a finite element model of the structure. Once the surface unknowns have been computed, the acoustic pressure anywhere in the fluid field can then be found using the exterior Helmholtz Equation [6,7].

In the current version of the code, AVAST provides a wide range of modelling features related to time-harmonic acoustic radiation. These include:

- Various fluid elements
  - three-noded triangular acoustic panel
  - four-noded quadrilateral acoustic panel
  - eight-noded quadrilateral isoparametric acoustic element
- Multiple body models
- Model size reduction using X-Y, Y-Z and X-Z planes of symmetry
- Various fluid domains
  - half-space
  - infinite
  - finite depth
- Eigenvalue analysis
- Frequency response analysis
- Exterior fluid field pressure evaluation
- Stop/restart capability

For the analysis of time-harmonic acoustic radiation, the AVAST suite of programs uses VAST [8] as a basis to establish the modal characteristics of the "dry" structure. By adopting the mode shapes and natural frequencies of the dry structure, the governing equation of motion for the coupled fluid/structure system is converted into a generalized coordinate system having the form,

$$\left([\Omega] - \omega^2[I] - \omega^2[\Phi]^T[M_a(\omega)][\Phi] + i\omega[\Phi]^T[C][\Phi]\right)\{u\} = \{q\} \qquad (1.1)$$

where:

$[\Phi]$ represents a matrix whose columns are the dry structural mode shapes orthogonalized with respect to the structural mass matrix

ω_i represents the i-th natural frequency of the dry structure

$$[\Omega]_{ij} = \begin{cases} 0 & i \neq j \\ \omega_i^2 & i = j \end{cases}$$

$\{u\}$ represents a vector of generalized displacements

$\{q\}$ represents a vector of generalized forces

$[C]$ represents the structural damping matrix

ω represents the forcing frequency

$[M_a(\omega)]$ represents the frequency dependent acoustic added mass matrix

Once the surface displacements have been computed using Equation (1), the surface acoustic pressures may then be generated using the Surface Helmholtz Equation [7] and the exterior field pressures via the Exterior Helmholtz Equation [7].

1.2 How to Use the AVAST System

Since AVAST is based on a combination of the finite element and boundary element methods, users should have some knowledge of these methods before attempting to use the system. For general background on the computational method, the reader should consult one of the many excellent text books on the subject such as the one by Beer an Watson [11].

An AVAST analysis will generally consist of the following steps:

i. Structural finite element modal analysis using VAST;
ii. Fluid boundary element idealization;
iii. Preparation of input data;
iv. Program execution;
v. Examination of computer results; and
vi. Graphical displaying of results.

Structural modelling (Step i) is a very important part of any AVAST analysis. It includes the selection of proper element types and element mesh. Usually, this requires some degree of skill on the part of the user.

Fluid boundary element idealization (Step ii) is also a critical part of any analysis. It includes the selection of the proper acoustic element type, fluid domain type and acoustic medium properties (density and sound speed). This too requires some degree of skill on the part of the user.

Input data requirements are described in Section 3 of the manual.

A general discussion on the types of analyses which AVAST can perform and important aspects of finite element/boundary element modelling is found in Section 2. **It is mandatory that the user read and understand this section before using the program.**

The units of length (inches, centimetres, etc.) and force (pounds, Newtons, etc.) must be consistent throughout the entire data. The unit of time of seconds is used throughout.

1.3 How to Run the AVAST System

With certain exceptions, the input goes on a main data set file, called PREFX.BEM. However, if exterior field acoustic pressures are to be calculated, the coordinates of the field points must be placed in a separate file (PREFX.EFP). After the input data file(s) have been prepared according to the format outlined in Section 3, the AVAST system can be run to perform the acoustic radiation analysis.

2. GENERAL

2.1 Introduction

The method used in AVAST to solve the fluid-structure interaction problem is to model the structural motion using the finite element method and the acoustic field with an integral equation formulation. Boundary integral formulations are well-suited to problems where the domains extend to infinity but where the governing equations are linear and homogenous, while the finite element method is most effective when restricted to bounded domains but is applicable to problems with non-homogenous materials and where non-linearities may occur.

In the current version of AVAST (Version 6.1), specialized algorithms have been adopted in order to consider the problem of computing the frequency response and natural frequencies of a linear elastic structure in contact with an acoustic medium. The development of these algorithms was prompted by a recent study [7] which reviewed a number of numerical methods commonly used to predict the radiated noise generated by submerged elastic structures. In order to evaluate the performance of the different numerical schemes, predictions were compared to both analytical and experimentally measured results. These tests showed that methods which exploited the eigenvalues and associated eigenmodes of the "wet" structure provide a more accurate assessment of the radiated noise patterns than do other techniques. This was especially true when the structure was loaded at a resonant frequency.

The most fundamental difference between this latest version of AVAST and previous versions lies in the method used to couple the fluid and structural equations of motion. In Version 5.0, the fluid is introduced into the structural equation through an equivalent "frequency dependent acoustic added mass" term [5]. This leads to the following governing equation for the frequency response of the coupled fluid structure system,

$$\left([K] - \omega^2\left[M_s + M_a(\omega)\right] + i\omega[C]\right)\{\delta\} = \{f\} \tag{2.1}$$

where $\left[M_a(\omega)\right]$ represents the frequency dependent acoustic added mass matrix, $[K]$ represents the structural stiffness matrix, $[C]$ represents the structural damping matrix, $\left[M_s\right]$ represents the structural mass matrix and $\{f\}$ represents a vector of nodal structural forces.

In order to speed up processing in the current version of the AVAST code, the frequency dependence of the acoustic added mass term is eliminated by substituting the original matrix with a set of three acoustic mass matrices evaluated at frequencies (ω_1, ω_2 and ω_3) which span a user-defined frequency range. For example, if the frequency response range of interest lies between the frequencies ω_a and ω_b (where $\omega_a <= \omega_b$), the acoustic added mass matrix $\left[M_a(\omega)\right]$ is approximated by the following series,

$$[M_a(\omega)] = [M_a(\omega_0)] + \omega[M_a(\omega_1)] + \omega^2[M_a(\omega_2)] \tag{2.2}$$

where $\omega_a < \omega_0 < \omega_1 < \omega_2 < \omega_b$

As a result, Equation (2.1) can be rewritten in the following form,

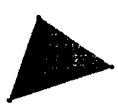
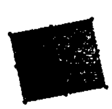
$$\left([K] - \omega^2[M_s] - \omega^2\left([M_a(\omega_0)] + \omega[M_a(\omega_1)] + \omega^2[M_a(\omega_2)]\right) + i\omega[C]\right)\{\delta\} = \{f\} \tag{2.3}$$

The most fundamental and generally the most costly part of an AVAST analysis is the formulation of the acoustic added mass matrices, which involves a number of matrix operations including the decomposition of a series of complex, fully populated and nonsymmetric matrices.

2.2 Element Library

AVAST provides the user with a choice of three fluid panel types (see Table 2.1): a three-noded triangular constant pressure panel, a four-noded quadrilateral constant pressure panel, and an eight-noded isoparametric fluid panel. It is important to note, however, that any one model cannot use more than one type of fluid panel. It is also recommended that users attempt to model the wet structural surface with compatible structural and fluid element/panel types.

TABLE 2.1: Element Library

Element	Description	Element Code (IEC)	Number of Nodes
	Triangular constant pressure panel	1	3
	Quadrilateral constant pressure panel	3	4
	Isoparametric panel	2	8

2.3 Eigenvalue Analysis (Natural Frequency)

The governing equation for an AVAST natural frequency analysis has the following form,

$$\left([K] - \omega^2[M_s] - \omega^2[M_a(\omega_0)] - \omega^3[M_a(\omega_1)] - \omega^4[M_a(\omega_2)]\right)\{\delta\} = \{0\} \tag{2.4}$$

By adopting the mode shapes and natural frequencies of the dry undamped structure (computed by VAST), the governing equation of motion for the coupled system is converted into a generalized coordinate system having the form,

$$\left([\Omega] - \omega^2[I] - \omega^2[\Phi]^T\left([M_a(\omega_0)] + \omega[M_a(\omega_1)] + \omega^2[M_a(\omega_2)]\right)[\Phi]\right)\{u\} = \{0\} \tag{2.5}$$

where $\{u\}$ represents a vector of generalized displacements $([\Phi]\{u\} = \{\delta\})$.

The solver used to compute the natural frequencies of the assembled equation given above is the LAPACK routine ZGEGV [9], which uses the QZ algorithm [10].

2.4 Frequency Response Analysis

The frequency response analysis option in AVAST provides a solution for the steady state structural displacements and wet surface fluid pressures of the coupled fluid/structure system when subjected to a set of sinusoidal loads of known amplitudes and frequencies. Loads are specified as amplitudes and can consist of concentrated forces and pressures.

The governing equation for the frequency response of the coupled fluid/structure system has the form given below.

$$\left([K] - \omega^2[M_s + M_a(\omega)] + i\omega[C]\right)\{\delta\} = \{f\} \tag{2.6}$$

where $[M_a(\omega)]$ is the frequency dependent acoustic added mass matrix and $\{f\}$ represents a vector of structural nodal forces.

By adopting the mode shapes and natural frequencies of the dry structure, the governing equation of motion for the coupled system can be converted into a generalized coordinate system having the form,

$$\left([\Omega] - \omega^2[I] - \omega^2[\Phi]^T[M_a(\omega)][\Phi] + i\omega[\Phi]^T[C][\Phi]\right)\{u\} = \{q\} \tag{2.7}$$

where $\{q\}$ represents the applied structural load transformed into the generalized coordinate system. Equation (2.7) can be simplified by restricting the structural damping to have the following form,

$$[C] = \alpha_k[K] + \alpha_m[M_s] \tag{2.8}$$

Substituting Equation (2.8) into (2.7) then yields,

$$\left((1+i\omega\alpha_k)[\Omega]-\omega^2\left(1-\frac{i\alpha_m}{\omega}\right)[I]-\omega^2[\Phi]^T\left[M_a(\omega)\right][\Phi]\right)\{u\} = \{q\} \tag{2.9}$$

Solving for the generalized displacements using Equation (2.9) then yields the following expression,

$$\{u\} = [A]\ \{q\} \tag{2.10}$$

where the matrix [A] may be defined as,

$$[A] = \left[(1+i\omega\alpha_k)[\Omega]-\omega^2\left(1-\frac{i\alpha_m}{\omega}\right)[I]-\omega^2[\Phi]^T[Ma(\omega)][\Phi]\right]^{-1} \tag{2.11}$$

3. INPUT DATA

Notes:

(1) The input data contains:

(i) Header data, described in this section.

(ii) Geometry, element data, and data for natural frequency calculations (Section 3.1).

(iii) Data for frequency response calculations (Section 3.2).

(iv) Data for exterior field point calculations (Section 3.3).

(2) The units of measurement must be consistent throughout the entire data. Selected units in English and metric systems are given in Table A-1, Appendix A.

(3) A five character literal constant (PREFX) used to prefix AVAST input and output file names is required.

(4) Structural loads must be available on a VAST compatible T49 file.

(5) Modal data corresponding to the "dry" structure must be available on a VAST compatible T51 file.

Header data

Card 1 (I5)

ICEIG = 0, restart (coupled natural frequencies have been computed during a previous run).

= 1, coupled natural frequencies are computed.

Card 2 (I5)

ICFQR = 0, restart (structural displacements and wet surface acoustic pressures have been calculated during a previous run).

= 1, modal frequency response is calculated at all coupled resonant frequencies.

Card 3 (I5)

IEFP = 0, do not compute exterior field pressures.

= 1, exterior field pressures are computed.

3.1 Fluid Geometry and Coupled Natural Frequency Analysis (ICEIG = 1)

Notes:

(1) AVAST uses the data described in Section 3.1 to generate the fluid matrices resulting from the discretization of the fluid domain via the boundary integral equation method. Data provided in this section is also used by AVAST to compute the natural frequencies of the coupled fluid/structure system.

(2) Execution speeds are highly dependent on the value selected for the integration order (NIP) and the number of modes used to model the structural response.

(3) Upon successful completion of this portion of the analysis, output in the form of the coupled natural frequencies is placed in a file having the name PREFX.EVL.

Card 1a (I5)

NSB = the number of structural bodies to be included (100 maximum).

Provide Card 1b NSB times

Card 1b (A5)

PREFX = five character literal constant to prefix AVAST file names. Note that the prefix corresponding to the first body is used to define all other AVAST input and output files.

Card 2 (I5)

NIP = number of Gauss integration points used to compute the elements of the matrices generated by the boundary integral equation method (1 < = NIP < = 20).

Card 3 (2E10.3)

C = fluid sound speed.

RHO = fluid density.

Card 4 (2E10.3)

FREQ1 = frequency (in Hz) defining the lower bound of the frequency range over which the acoustic mass matrix is interpolated.

FREQ2 = frequency (in Hz) defining the upper bound of the frequency range over which the acoustic mass matrix is interpolated (FREQ1 $<=$ FREQ2).

Card 5 (I5)

IPS = 0, no symmetry with respect to the fluid model is assumed.
= 1, fluid symmetry with respect to the X-Z plane is assumed.
= 2, fluid symmetry with respect to the Y-Z plane is assumed.
= 3, fluid symmetry with respect to both the X-Z and Y-Z planes is assumed.

Card 6 (I5)

IFD = 0, an infinite fluid domain is assumed.
= 1,a half-space fluid domain is assumed.

Card 7 (I5) (omit if IFD = 0)

IHSB = 1, fluid half-space is assumed to represent a free surface.
= 2, fluid half-space is assumed to represent a rigid surface.

Card 8 (I5) (omit if IFD = 0)

ZHSB = Z coordinate of plane representing the fluid half-space.

The remaining cards (9-13) used to described the fluid model geometry (the wet surface of the structure) are read in from the file called PREFX.BEM.

Card 9 (A72)

TITLE = 72 character subtitle identifying the geometry and element data.

Card 10 (I5)

NFN = the number of nodes used to describe the geometry.

Provide Card 11 NFN times

Card 11 (I5,3E10.3)

NI = fluid node number.

XCO = X coordinate of node NI (length).
YCO = Y coordinate of node NI (length).
ZCO = Z coordinate of node NI (length).

Card 12 (2I5)

IEC = fluid panel code (see Table 2.1). A model may contain only one element type.

NPAN = number of fluid panels in the model.

Provide Card 13a NPAN times (omit if IEC is not equal to 1)

Card 13a (3I5)

N1 - N3 = the three nodes which make-up the connectivity for the three-noded constant pressure fluid panel (see Figure 3.1). Note that the nodes must be numbered in a counter-clockwise orientation as viewed from the fluid (panel normals must be directed into the fluid).

Provide Card 13b NPAN times (omit if IEC is not equal to 2)

Card 13b (8I5)

N1 - N8 = the eight nodes which make-up the connectivity for the eight-noded isoparametric fluid panel (see Figure 3.2). Note that the nodes must be numbered in a counter-clockwise orientation as viewed from the fluid (panel normals must be directed into the fluid).

Provide Card 13c NPAN times (omit if IEC is not equal to 3)

Card 13c (4I5)

N1 - N4 = the four nodes which make-up the connectivity for the four-noded constant pressure fluid panel (see Figure 3.3). Note that the nodes must be numbered in a counter-clockwise orientation as viewed from the fluid (panel normals must be directed into the fluid).

Card 14 (2I5)

NM1 = number of the first dry structural mode to be used in the generation of coupled natural frequencies.

NM2 = number of the last dry structural mode to be used in the generation of coupled natural frequencies (NM1 <= NM2).

Card 15 (E10.3)

CUTOFF = tolerance used for determining whether the magnitude of the imaginary component of a computed coupled natural frequency is too large. If a natural frequency generated by AVAST has an imaginary component larger in magnitude than CUTOFF that frequency is discarded.

3.2 Coupled Frequency Response Analysis (ICFQR = 1)

Notes:

(1) AVAST uses the data provided in this section (3.2) to compute the steady state displacements and surface acoustic pressures generated by a sinusoidal load, where the amplitudes of the loads are the static loads generated by the VAST LOAD module (stored in file PREFX.T49). The steady state displacements and pressures are calculated for forcing frequencies equal to the natural frequencies of the coupled fluid/structure system.

(2) Upon successful completion of this portion of the analysis, output in the form of the steady state structural displacements are placed in a file having the name PREFX.SGD. In addition, output in the form of steady state acoustic pressures are stored in a file having the name PREFX.PRS.

Card 1 (A5)

PREFX = five character literal constant to prefix AVAST file names.

Provide Card 2 as many times as required

Card 2 (8E10.3)

DRATIO = damping ratio for each of the coupled natural frequencies. Admissible range: 0.0 (no damping) to 1.0 (100% of critical viscous damping).

3.3 Exterior Field Pressure Analysis (ICEFP = 1)

Notes:

(1) AVAST uses the data described in Section 3.3 to compute steady state exterior field acoustic pressures. These field pressures are generated using the steady state structural displacements stored on an AVAST compatible PREFX.SGD file

and the wet surface acoustic pressures stored on an AVAST compatible PREFX.PRS file.

(2) Upon successful completion of this portion of the analysis, output in the form of the steady state exterior field pressures are placed in a file having the name PREFX.FPR.

Card 1 (I5)

NEFP = the number of exterior field point locations.

Provide Card 2 NEFP times

Card 2 (I5,3(2X,E12.6))

NEI = exterior field point number
XCO = X coordinate of node NEI (length).
YCO = Y coordinate of node NEI (length).
ZCO = Z coordinate of node NEI (length).

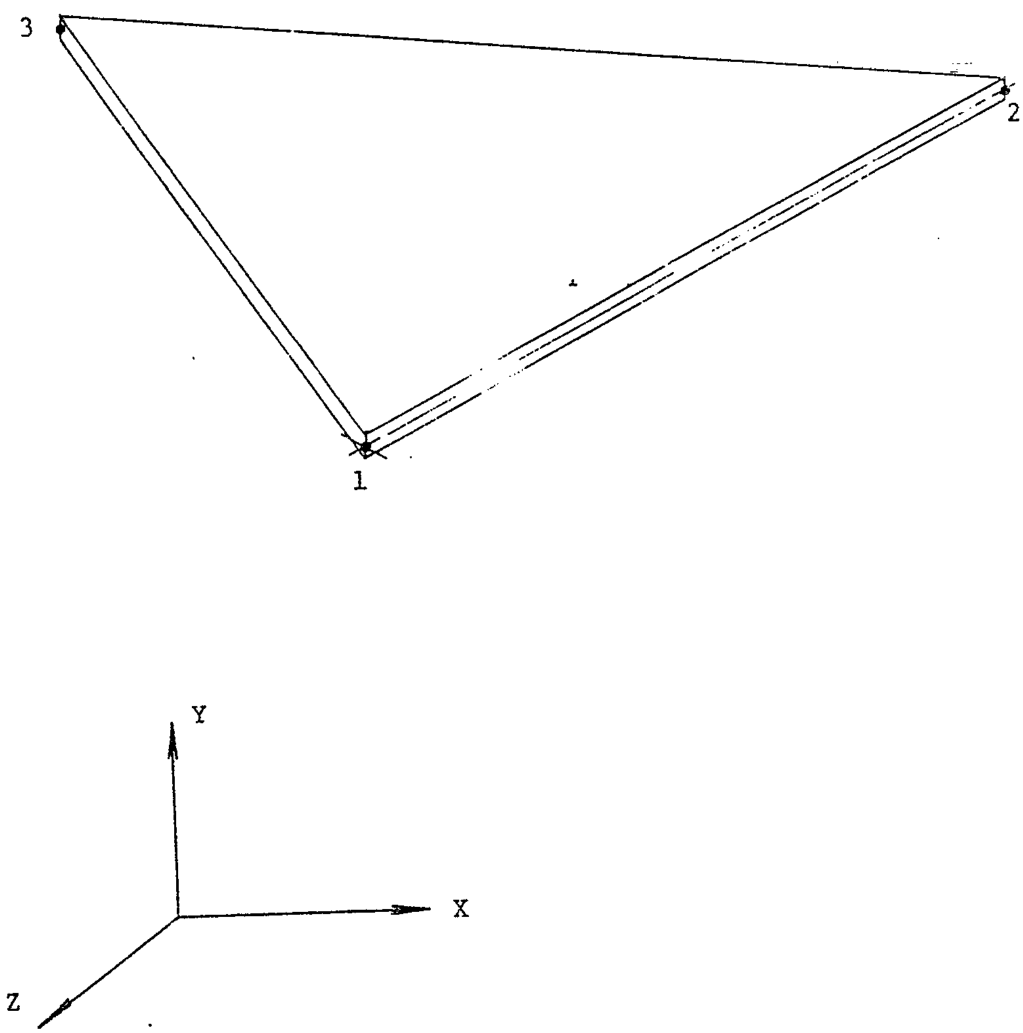


FIGURE 3.1: Modelling Convention for the Three-Noded Fluid Panel

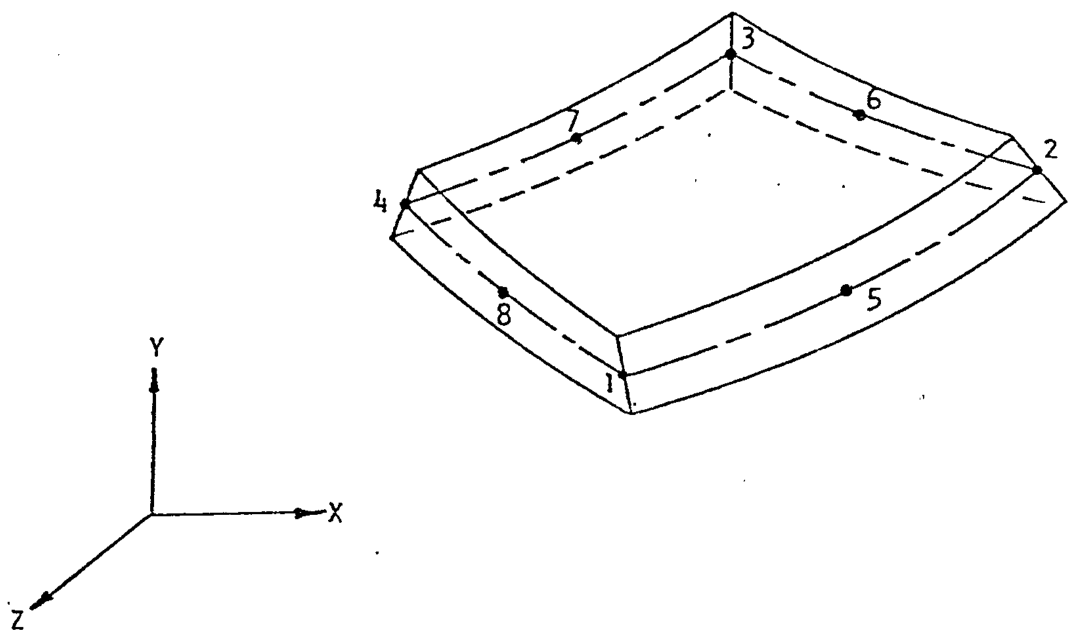


FIGURE 3.2: Modelling Convention for the Eight-Noded Fluid Panel

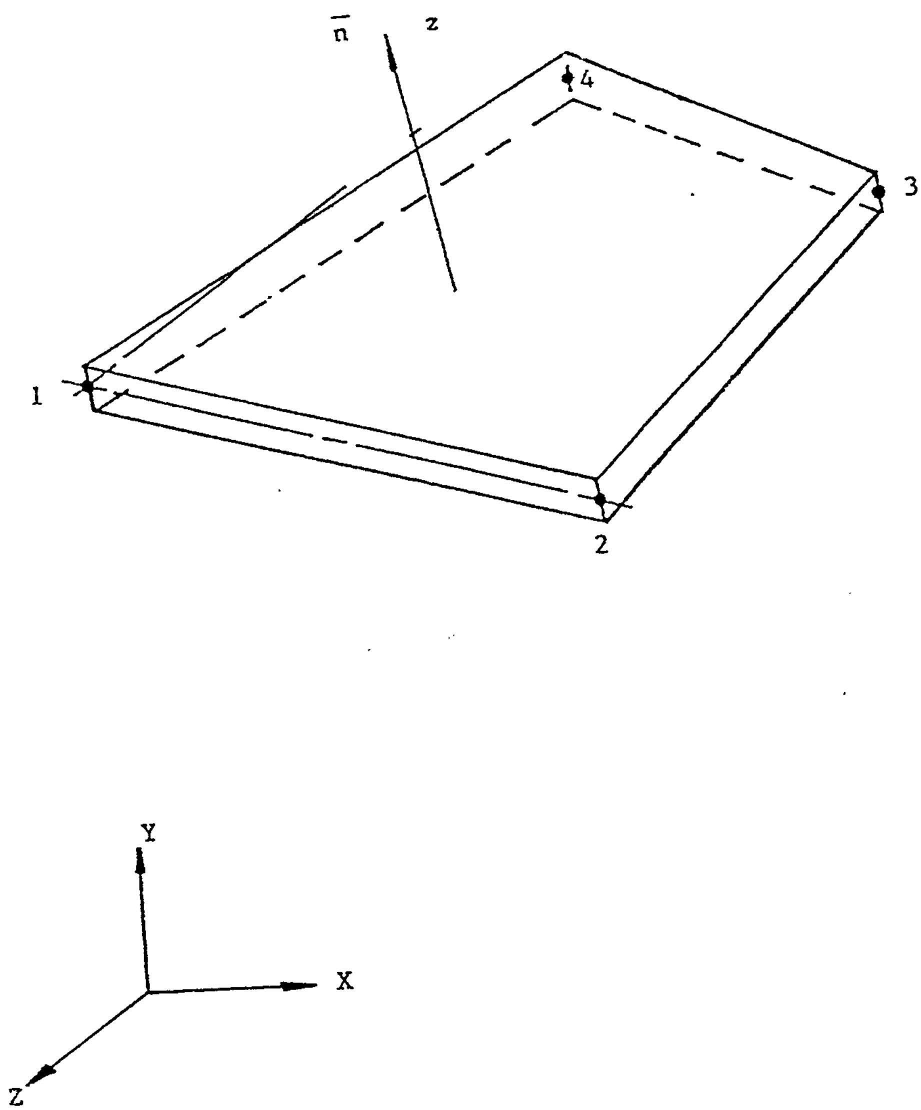


FIGURE 3.3: Modelling Convention for the Four-Noded Fluid Panel

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APPENDIX A:

UNITS

TABLE A-1: Selected Units in English and Metric

Quantity	English		Metric	
	Units	Unit Name	Units	Unit Name
Area	in^2	square inches	mm^2	square millimetres
Force or Weight	lb	pound	N	Newton
Length	in	inch	mm	millimetre
Mass	$lb.sec^2/in$	weight/ acceleration of g	$N.sec^2/mm$	weight/ acceleration of g
Weight Density	lb/in^3	pound per cubic inch	N/mm^3	Newton per cubic millimetre
Mass Density	$lb.sec^2/in^4$	weight density/ acceleration of g	$N.sec^2/mm^4$	weight density/ acceleration of g
Modulus of Elasticity (Young's or Shear)	lb/in^2	pound per square inch	N/mm^2 or (MPa)	Newton per square millimetre (megaPascal)
Moment of Force	lb.in	pound inch	N.mm	Newton millimetre
Moment of Inertia	in^4	inch to fourth power	mm^4	millimetre to fourth power
Pressure and Stress	lb/in^2	pound per square inch	N/mm^2 or (MPa)	Newton per square millimetre (megaPascal)
Time	sec	second	sec	second
Torque	lb.in	pound inch	N.mm	Newton millimetre

APPENDIX B:

RUNNING AVAST ON THE DREA WARRIOR SYSTEM

RUNNING AVAST ON THE DREA WARRIOR SYSTEM

On the DREA Warrior system, the AVAST executable code is stored on directory /hy8/avast. AVAST execution may be initiated by entering the following command:

/hy8/avast/avast5

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A user's manual for finite element/boundary element program AVAST is presented. A brief introduction to the procedures incorporated into AVAST is given. The various analysis options are described and operating instructions, including a detailed description of data input and running procedures for RISC-based computer systems, are provided.

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